# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

ed to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and lection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, on Project (0704-0188), Washington, DC 20503.

AD-A223 962

2. REPORT DATE
July 1990

3. REPORT TYPE AND DATES COVERED
professional paper

4. TITLE AND SUBTITLE
CLOUD MODELING REQUIREMENTS OF PULSED LASER COMMUNICATIONS SYSTEMS

5. FUNDING NUMBERS
PE: 0601000N
WU: DN307474
PR: CM06

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Ocean Systems Center
San Diego, CA 92152–5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Pulsed laser communication systems have been proposed which work through all types of clouds. Predicting the performance of such systems requires a knowledge of the statistics of the spatial, angular and temporal spreading of pulses by clouds. Current models are particularly weak in predicting pulse transmission/reflection when the transmitter is near the horizon with respect to the receiver. A database consisting of the probability of cloud pattern types has been developed to be used with a database of cloud pattern properties. Together these two databases are used to predict system performance statistics for operational scenarios. In the future, real-time operational planning for message delivery will require short term predictions of cloud fields and their effects on performance. Models of reflection of pulses from clouds, as well as transmission through them are needed to make accurate evaluations of the probability of interception and disclosure of receiver or transmitter position.



Published in *Proceedings of CIDOS 89/90* Conference, January 1990.

14. SUBJECT TERMS
CIVAPP
astronomy
optical detectors

15. NUMBER OF PAGES

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | SAME AS ABSTRACT |

# CLOUD MODELING REQUIREMENTS OF PULSED LASER COMMUNICATIONS SYSTEMS

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## ABSTRACT

Pulsed laser communication systems have been proposed which work through all types of clouds. Predicting the performance of such systems requires a knowledge of the statistics of the spatial, angular and temporal spreading of pulses by clouds. Current models are particularly weak in predicting pulse transmission/reflection when the transmitter is near the horizon with respect to the receiver. A database consisting of the probability of cloud pattern types has been developed to be used with a database of cloud pattern properties. Together these two databases are used to predict system performance statistics for operational scenarios. In the future, real-time operational planning for message delivery will require short term predictions of cloud fields and their effects on performance. Models of reflection of pulses from clouds, as well as transmission through them are needed to make accurate evaluations of the probability of interception and disclosure of receiver or transmitter position.

## 1. INTRODUCTION

Over the last few years several experiments which have demonstrated pulsed laser communications through clouds and sea water to a submarine (Morgiewicz et al. 1987; Maurer, 1986; Titan Systems and Naval Ocean Systems Center 1987; Bradley et al. 1988).

One system proposed to use laser communications to a submerged receiver was the Satellite Laser Communications, SLC, system. This was a satellite to submarine downlink which was recently struck from the budget for a major flaw, it was too expensive. Even though the SLC system was canceled, the work done has given people an awareness of a new type of communications link with novel properties. It is likely that future communications systems will be proposed using this type of link.

Whatever these systems might be, it will be necessary to evaluate how the range of possible cloud and water conditions affect their performance. Ideally the evaluation would be accomplished by using the system at various locations around the world and over an extended period of time. This would allow a wide range of conditions can be tested. Economics dictates that this will not happen until a system is in the fleet. It costs too much to maintain a transmitter above the clouds, a receiver beneath the water and crews of people standing by waiting for the weather to change. An experiment could easily run as long as a month and only gather statistically significant information on only a few cloud pattern types. Seasonal information would require repeats of such expeditions throughout the year. Therefore a documented, defensible model is a necessary tool for evaluating a laser communication system.

Given that laser communication system performance is sensitive to the clouds present, predictions of system performance at oceanic locations around the world depend upon meteorological databases to supply reasonable cloud frequencies and cloud characteristics as system model inputs. Such a model can be used to estimate how much availability would be lost by building a system which tolerates something less than the worst possible cloud conditions. This information is needed to make system cost/performance trade-off studies.

Operational laser communications systems will need real-time predictions of performance to aid communications planning. Two candidate ways of doing this include: (1) using meteorologists' cloud predictions in conjunction with databases describing performance through all types of clouds or (2) using backscattered solar radiance measurements to predict cloud losses.

## 2. CURRENT MODELS OF PULSE SNR

To predict signal-to-noise ratio our present model requires cloud optical and physical thickness, cloud base height and cloud thickness-to-height ratio. The model is relatively insensitive to cloud base height over the range of reasonable values. Our approach has been to divide the cloud pattern types of the world into six categories: open cell, closed cell, stratus, multi-layer, tropical cyclone and towering cumulus. For each category we have collected statistics on frequency of occurrence, optical thickness and physical thickness as a function of location and season.

The cloud pattern frequency of occurrence data was generated by a meteorologist who visually estimated percentages of each of the cloud patterns in each of 38 regions of the northern hemisphere oceans from visible and infrared satellite images. Cloud pattern frequency was determined once a week for 1982 (SRI, 1988) and once a month for 1974 - 1976 (Allen et al. 1985).

Optical thickness statistics were generated for each cloud pattern type from solar irradiance data (Table 1). An algorithm developed by Waldman, et al. (1989) was used to estimate the equivalent optical thickness of a uniform thickness, horizontally infinite cloud which would yield the measured irradiance. The optical thickness computed is a function of sun zenith angle at the time of the measurement. The type of cloud pattern responsible for the measured optical thickness was determined from satellite images.

The preceding databases are used in the SLCEVAL (Rockway et al. 1988; James 1988) program which allows the user to specify receiver location, depth, date, time-of-day, transmitter parameters and receiver parameters. The program makes Monte Carlo runs which randomly draw cloud and water conditions appropriate for the receiver and transmitter locations and time of year input. The output is a distribution of message delivery times.

With the type of system modeled by SLCEVAL it is impractical to continuously adjust beam intensity to local conditions while scanning. Therefore the optical thickness used in making calculations was the 95% point on the cumulative optical thickness curve for the chosen cloud pattern type. This was done to guarantee connectivity to most of the area. Some laser communications architectures would require different methods of choosing optical thickness.

For computing the pulse width of stratus clouds, SLCEVAL uses a curve fit (Eq. 1) to the results of a Monte Carlo cloud simulation which assumes a homogeneous cloud having a flat top, a flat bottom and which is horizontally infinite (James 1988).

$$\Delta t_c = \frac{1.15x10^{-6}\tau^{2.61}(Z+94)^{\alpha}(H+65)^{\beta}}{0.0025\tau^{1.85}+1} \qquad (1)$$

with

$$\tau = Z/D$$

$$\alpha = 1.05(1-e^{-0.0655\tau^{0.981}}) + 1.01e^{-0.246\tau}$$

$$\beta = 0.413\tau^{0.545}e^{0.0764\tau}$$

Table 1. Locations for which solar irradiance data has been converted to optical thickness distributions.

| MEASUREMENT LOCATION | REFERENCE | MEASUREMENT LOCATION | REFERENCE |
|---|---|---|---|
| Canada | Monahan et al. 1987b | Puerto Rico | Monahan et al. 1989 |
| Alert | | San Juan | |
| Cape St. James | | Sweden | Monahan et al. 1989 |
| Halifax | | Ultuna | |
| Inukjuak | | United Kingdom | Monahan et al. 1988 |
| Ocean Weather Station P, 50N 145W | | Ocean Weather Ship | |
| | | A: 62N 33W | |
| | | I: 59N 19W | |
| Port Hardy | | J: 52N 22W | |
| Sable Island | | K: 45N 16W | |
| Sachs Harbor | | United States | |
| St John's | | Caribou, ME | Monahan et al. 1989 |
| Denmark | Monahan et al. 1989 | Fairbanks, AK | Monahan et al. 1987a |
| Copenhagen | | Honolulu, HI | Monahan et al. 1987b |
| Finland | Monahan et al. 1989 | Long Beach, CA | |
| Sodankyla | | Miami, FL | |
| Guam | Monahan et al. 1987 | Sterling, VA | |
| Iceland | Monahan et al. 1989 | Seattle, WA | |
| Reykjavik | | Tallahassee, FL | |
| Norway | Monahan et al. 1989 | | |
| Aas | | | |
| Berset | | | |
| Tromso | | | |
| Sola | | | |

In Eqs. (1,2) $\Delta t_c$ is the 3 db pulse width in microseconds, $\tau$ is the cloud optical thickness, $H$ is the cloud-base height or cloud bottom-to-ground spacing in meters, $Z$ is the cloud physical thickness in meters, $D$ is the mean free path of a photon in the cloud. Equation (1) is optimized for cloud physical thicknesses between 100 and 10,000 meters, cloud base height between 100 and 8000 meters and cloud optical thicknesses between 5 and 100.

The results are similar to those of Bucher (1973) except that they fit the Monte Carlo results better for optical thicknesses below 20. For cloud pattern types other than stratus, the pulse lengths Eq. (1) computes are much longer than were measured in cloud field tests (Morgiewicz et al. 1987). This is believed to be due to finite cloud effects (Lee and Schroeder 1987; Waldman, 1989; Yen, this conference). Therefore, except for stratus, we use a relation (Eq. 2) developed by Lee and Schroeder (1987) from Monte Carlo results for pulse width beneath an isolated cylindrical cloud.

$$\Delta t_c = \omega_0 \left\{ \frac{\alpha_1}{\left(\frac{Z}{D}\right)^{\alpha_3} + \alpha_1} \right\}^{\alpha_2} \qquad (2)$$

with

$$\omega_0 = 1.415x10^{-9} Z\sqrt{\tau}$$

$$\alpha_1 = \frac{1.46*10^4 \tau^{0.715}}{(\tau + 359)^{2.18}}$$

$$\alpha_2 = \frac{1.18\tau}{\tau + 0.872}$$

$$\alpha_3 = 1.65(\tau^{-4.61} + 0.887)$$

The variable $(Z/D)$ in Eq. (2) is the cloud height over diameter ratio. The physical dimensions used for the cloud pattern types were taken from the descriptions in the literature of the thickest clouds typical of the cloud pattern types (Serebreny, 1987). Drawing from a distribution of physical thickness would be more appropriate for some types of communication systems. The optical thicknesses used were those described above.

More recent Monte Carlo simulations of finite clouds (Waldman, 1989) indicate that Lee and Schroeder (1987) (Eq. 2) slightly over estimates pulse width. They evidently assumed a receiver capable of intercepting all photons hitting the water.

There are problems with how the SLCEVAL program uses the above equations. In most cloud patterns neither the assumption of isolated clouds used by Lee and Schroeder (Eq. 2) nor the assumption of uniform thickness clouds (Eq. 1) is met. Some cloud patterns are more complex than either of the above models and have multiple layers as well as towering clouds. In addition the optical thicknesses used by the model were derived from solar irradiance data with equations that assume clouds are uniform and horizontally infinite.

## 3. IMPROVING MODELS OF PULSE SNR

The work of others suggests that complex cloud fields have significantly different optical properties than a single layer cloud field. Features of finite clouds which are different from single layer clouds include: light can escape from or enter on a side, shading of one cloud by another, large delays between scattering events for photons going from cloud to cloud.

Several authors have dealt with solar reflection and transmission of fields of finite clouds. The relationships between reflection/transmission and solar zenith angle are different for fields of finite clouds than they are for a uniform semi-infinite cloud layer (Kobayashi, 1988; Coakley and Davies 1986; Ebel and McKee 1983). Light which has undergone only a few scattering events tends to be preferentially forward scattered. As a result, when the sun is directly overhead, more sunlight is transmitted by the cloud field because light escaping the sides of the clouds is more likely to go down than up. When the sun is near the horizon, cloud sides intercept much of the sun's light. More light is subsequently scattered out the top of the field and less is transmitted through it than would be the case for the equivalent uniform cloud layer. Factors which affect the total amount of upwelled and downwelled light by a field of non-uniform clouds includes cloud coverage, shape, size, spacing, composition and size distribution of the scattering particles in the cloud, sun zenith angle, and wavelength of the light being considered.

Though much work has been done on fields of finite clouds by people interested in climate and the earth's radiation budget, there are significant differences between their concerns and those of a laser communication system. When dealing with climate, total upwelled and downwelled light is important. Since a receiver can be anywhere with respect to the cloud field, spatial distribution of signal-to-noise ratio is important. A climatologist can average over days, but a communication system cares about now. Because a laser transmitter and the sun are unlikely to be directly in line with each other, their signals do not vary together. The laser signal is a pulsed rather than constant signal.

Cloud non-uniformity affects pulse shape as well as transmission. Light which goes through the thin spots in a cloud field is delayed less than that which goes through the thicker spots. This increases energy in the early part of the received laser pulse and decreases the pulse width. Signal-to- noise ratio of a pulse signal is approximately proportional to the pulse width when determined after an optimal matched filter. Thin spots in the clouds improve the signal-to-noise ratio in two ways: (1) by increasing the transmission of the cloud field, and (2) by decreasing the pulse width of the signal. As a result of the above effects, the thin parts of a cloud field can be more important than the thick parts, even if they are only a small percentage of the field.

Because pulse shape affects signal-to-noise ratio, in addition to total energy transmitted, cloud fields with the same transmission can yield a range of signal-to-noise ratios. Defining this range of signal-to-noise ratio for a given overall optical thickness is one way to better understand and remove errors which would otherwise be introduced by using optical thicknesses derived from solar irradiance.

In an attempt to gain a better understanding of how to relate solar irradiance statistics taken beneath complex fields of mixed cloud types to laser pulse signal-to-noise ratio, Monte Carlo studies of pulse transmission through isolated cubic clouds have been performed (Waldman, 1989; Yen, this conference; Wills, 1988). Next, we plan to model fields of cubic clouds beneath which there will be an array of solar irradiance receivers and laser pulse receivers. By using simulated cloud fields which approximate our set of six cloud pattern types and which are constrained to produce solar irradiance distributions similar to those we've measured, we hope to make better and more defensible estimates of pulse length and transmission statistics for the cloud pattern types.

Validation of the results from the above cubic cloud field model is going to be difficult. Ideally one would hold a field test in which pulses were transmitted through clouds to a receiver on the ground. Then a model equivalent to the actual cloud field would be built by arranging cubic clouds. Pulse signal-to-noise ratios would be compared between the model and the field test. The difficult (impossible?) part of such a plan is determining a correct three dimensional description for the cloud field during the period that the pulses are being received. The cloud sampling problem is made more difficult by the clouds changing significantly over periods of a few minutes. Typically the transmitter is not in the same direction from the receiver as the sun, therefore the equivalent optical thickness, is not the same for the sun and the laser. To further complicate matters, the laser spot laid down on the top of the cloud field from a field test platform will likely be a few kilometers across and therefore, unlike the sun, will not be illuminating all of the clouds in the field of view of the receiver.

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